TECHNICAL REPORT NO. 6-570

DURABILITY AND BEHAVIOR OF PRESTRESSED CONCRETE BEAMS

Report 5

LABORATORY TESTS OF WEATHERED PRETENSIONED BEAMS

by

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June 1976

Report 5 of a Series

Approved For Public Release; Distribution Unlimited

Prepared for Office, Chief of Engineers, U. S. Army
Washington, D. C. 20314

Under Work Unit 01 04 01-31133

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report No. 6-570	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) DURABILITY AND BEHAVIOR OF PRESTRESSED CONCRETE BEAMS; Report 5, LABORATORY TESTS OF WEATHERED PRETENSIONED BEAMS		5. TYPE OF REPORT & PERIOD COVERED Report 5 of a series
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Edward F. O'Neil		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Concrete Laboratory P. O. Box 631, Vicksburg, Miss. 39180		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Work Unit 01 04 01/31133
11. CONTROLLING OFFICE NAME AND ADDRESS Office, Chief of Engineers, U. S. Army Washington, D. C. 20314		12. REPORT DATE June 1976
		13. NUMBER OF PAGES 37
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) WES-TR-6-570-5		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

(9) (6) (10) (11) (12) 41p. (14)

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Concrete beams
Concrete durability
Corrosion
Laboratory tests
Prestressed concrete
Pretensioning
Reinforcing steels
Tensile strength

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report is the fifth in a series describing a study which is being conducted to develop information on the durability of prestressed (pretensioned and posttensioned) concrete beams. This report describes tests and observations on two beams that had been exposed to severe weathering for 16 years in a flexurally loaded condition at the Treat Island, Maine, exposure station. This phase of the study was conducted in the same manner as that described in Report 3 of this series, and the beams used were the same as those
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SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

20. ABSTRACT (Continued).

from Treat Island described in Report 3, with the exception of the loading condition of the beams during the years of weathering.

The laboratory tests conducted on these beams consisted of examination and tensile testing of the steel prestressing (pretensioning) strands after removal from the beams and also tests to determine depths of carbonation and chloride penetration into the test beams.

The conclusions drawn from the tests conducted on these beams are as follows:

a. The steel prestressing strands were heavily corroded due to spalling of the concrete and detachment of the protective epoxy end pads. The corrosion was heaviest at the ends of the strands, but it was also heavy in some areas of the midportion of the strand.

b. The corrosion of the strands was so severe that of the eight strands tested in tension (four from each beam), none of the strands passed all of the ASTM tests for tensile strength or elongation under load.

c. The corrosion on the center wire of each strand was of the same intensity as that on the outer wires and had progressed the same distance into the beam.

d. In areas of heavy corrosion of the strand, there was no cement paste stuck to the strands; where the steel was only lightly corroded, there was cement paste stuck to the strands, thereby indicating that water had penetrated into the beam along the cement paste-steel interface where the bond had broken and then into the center wire through the outer wire.

e. Results of tests to ascertain depth of carbonation indicated that carbonation was not a factor in the corrosion of the steel.

f. Results of tests to ascertain the degree of chloride contamination revealed that there were sufficient chlorides present to be a major cause of corrosion of the prestressing strands.

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PREFACE

The investigation reported herein forms a part of Civil Works Research Work Unit 01 04 01/31133 and was approved by Office, Chief of Engineers, on 24 May 1974.

The test program was carried out by the Concrete Laboratory (CL) of the U. S. Army Engineer Waterways Experiment Station (WES), under the direction of Messrs. Bryant Mather, Chief of the CL, L. Pepper, Chief of the Engineering Sciences Division, and J. M. Polatty and J. M. Scanlon, former Chief and Chief, respectively, of the Engineering Mechanics Division. This report was prepared by Mr. Edward F. O'Neil.

Director of the WES during the conduct of this investigation and the preparation and publication of this report was COL G. H. Hilt, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	25.4	millimetres
pounds (force)	4.448222	newtons
pounds (force) per square inch	0.006894757	megapascals
gallons (U. S. liquid)	3.785412	cubic decimetres

DURABILITY AND BEHAVIOR OF PRESTRESSED CONCRETE BEAMS

LABORATORY TESTS OF WEATHERED PRETENSIONED BEAMS

PART I: INTRODUCTION

Background

1. This investigation was begun in 1956 to develop information on the durability and behavior of prestressed concrete beams. Reports 1-4 of this series[1-4] describe the test beams and the progress of this investigation through 1974. They include data on pretensioned beams weathered at the Treat Island, Maine, exposure station and at St. Augustine, Florida, and on posttensioned beams weathered at Treat Island. The pretensioned concrete beams used in the phase of the investigation reported herein were installed at the outdoor tidal exposure station at Treat Island in 1958 and 1959. The beams were subjected to freezing in air and thawing in seawater for 16 winters and inundated twice each day by the tides. Then they were returned to the Concrete Laboratory at the U. S. Army Engineer Waterways Experiment Station (WES) for examination and testing.

Purpose

2. The primary purpose of this phase of the investigation was to gather additional information on the condition of the prestressing strands from selected weathered beams returned to the WES from the Treat Island exposure station. Of primary interest was the condition of the central wire of each seven-wire prestressing strand and its effect on the surrounding wires with regard to passage of water into the center of the beam. One of the conclusions stated in Report 3 of this series was that "internal strand corrosion seemed to progress along the center wire from the ends of the beam and extended generally well beyond the external corrosion on the strands." The beams were also examined in the

same manner as that described in Report 3 of this series (Reference 3) in order to provide a basis for comparison of results obtained in these two phases of testing.

Scope

3. The work encompassed in this phase of the investigation included visual examination and laboratory testing of the concrete and the prestressing steel strands of beams 13 and 21 of the pretensioned beam series. The specific tests performed were as follows:

- a. Visual examination of the beams, including photographic recording of rusting, spalling, and staining.
- b. Examination and cataloging of the steel pretensioned strands to determine extent of corrosion.
- c. Structural testing of selected strands from each beam to determine tensile strength, elongation at failure, and the stress-strain characteristics of each strand.
- d. Tests for degree of chloride contamination.
- e. Tests for depth of carbonation.

PART II: DESCRIPTION OF TEST SPECIMENS

4. The pretensioned concrete beams in this study were of rectangular cross section (4-1/2 by 9 in.*) and were 81 in. long. Each beam contained nine 1/4-in. (1 by 7) prestressing strands located as shown in Figure 1. The beams were made of good quality air-entrained concrete

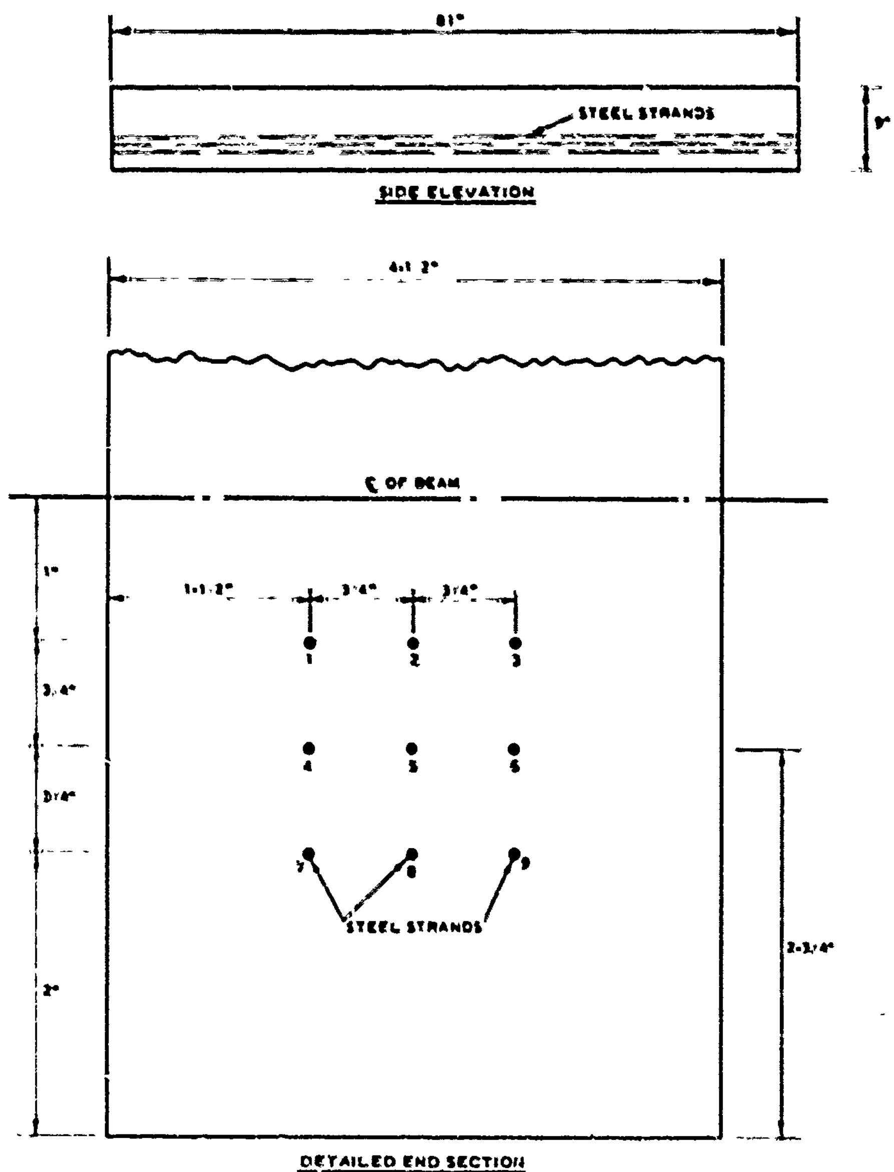

Figure 1. Detailed section of pretensioned concrete beam

* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

using limestone aggregates. Physical properties of the concrete mixture were:

Maximum Size Coarse Aggregate in.	Entrained Air, %	Nominal Compressive Strength at 28 Days, psi	Slump in.	Water-Cement Ratio gal/bag
3/4	4.5 ± 0.5	6000	1-3/4 ± 1/2	5.85

The ends of the steel strands were cut to be flush with the ends of the beams and were protected at each beam end with a pad of epoxy approximately 3 by 5 by 1/2 in. thick.

5. All the pretensioned beams included in this phase of the study were shipped to the WES from Treat Island at the time of this investigation, and beams 13 and 21 were chosen for testing. These beams had been installed at Treat Island in various loading conditions in October of 1958 and were returned to the laboratory at WES after 16 winters of tidal exposure. The pretensioning steel in both beams had been stressed to 70 percent of ultimate strength of the strand.

Beam 13

6. Beam 13 was loaded, as half of a yoked pair, to 6319 lb, which was 100 percent of prestress load. Photos 1a and 1b show the conditions of the landward and seaward ends, respectively, of this beam at the time it was received in the laboratory. As shown in these photos, both ends had received heavy damage due to spalling, thereby resulting in exposure of the strands to direct contact with the saline environment. Photo 2a shows the profile of the beam and the damage to the landward end. The seaward end was less damaged, but both ends of the beam had lost the epoxy pads that protected the ends of the strands. The edges of the beam showed moderate damage due to weathering of the concrete surface.

Beam 21

7. Photo 2b shows a profile of beam 21 as it was received from Treat Island. There is moderate to heavy damage due to weathering, and

the beam is cracked both at the landward and seaward ends and in the middle on the tension face. This beam was loaded to 5833 lb, which was 100 percent of the prestress load. Photos 3a and 3b show the deterioration of the landward and seaward ends, respectively. Both epoxy pads were missing, and at the ends moderate amounts of spalling had occurred, thereby exposing 1-3 in. of the strands to seawater corrosion. Comparison of Photos 3a and 3b shows that the corrosion at the landward end was more advanced than that at the seaward end.

PART III: TESTS AND RESULTS

Examination of the Strands

8. After photographs were taken to record the condition of the outside of each beam, the concrete was separated from the steel pretensioning strands. Photos 4a and 4b show the strands as they were being removed from the beams. The concrete around the strands of each beam (Photos 4a and 4b) broke into smaller pieces than did that at the top half of the beam, and in both beams the horizontal planes of the strands acted as planes of fracture when the concrete was broken. The ends of beam 13 are shown in Photos 5a and 5b. The strands show heavy rusting close to the ends where they were exposed when the concrete spalled. Also, in this area the concrete around the strands was stained with the products of corrosion. Farther into the beam where there was less rust on the strands, tere were fewer stains on the concrete. Photos 6a and 6b show the rust on the strands and rust stains on the concrete of beam 21 at the landward and seaward ends, respectively. Where the strands were heavily rusted, the concrete was heavily rust-stained, and where the strands were lightly rusted, similar rust stains occurred on the concrete.

9. Of the nine pretensioned strands in each beam, the four strands in the best condition were chosen for structural testing. The remaining strands were unraveled and the extent of corrosion on the strands recorded. Particular note was made of the extent of corrosion on the center wire with relation to that on the outside wires that surrounded it.

10. The locations of the steel strands in each concrete beam are shown in Figure 1. There are three strands in each of three rows: the strands in the row nearest the top of the beam as cast are numbered 1, 2, and 3; those in the middle row 4, 5, and 6; and those in the bottom row 7, 8, and 9. Each strand is a nominal 1/4-in.-diam strand consisting of seven wires, a center wire with six others surrounding it.

11. The terms used in evaluating the corrosion on the surface of

the steel strands from beams 13 and 21 are the same as those used and defined in Report 3 (Reference 3), thereby making possible a comparison between the results reported herein and those presented in Report 3. For convenience, terms and definitions are reproduced below.

Extent of Corrosion	Surface Area of Strand Coated with Corrosion Products, percent
Heavy	80-100
Moderate	30-80
Light	0-30

Heavy corrosion of the strands is shown in Photo 7a and light corrosion in Photo 7b.

12. The tests conducted on the pretensioned beams returned from Treat Island were as follows:

a. Examination of steel prestressing strands.

b. Determination of tensile strength and elastic properties of the steel strands.

c. Tests for depth of carbonation.

d. Tests for degree of chloride contamination.

Beam 13

13. The following subparagraphs describe the corrosion on the steel strands from beam 13.

a. Strand 1.

(1) Landward end: External corrosion extended for 7 in. from the end (0-4 in. = heavy; 4-7 in. = moderate).

(2) Seaward end: External corrosion extended for 9 in. from the end (0-2 in. = heavy; 2-9 in. = moderate).

(3) Rest of strand: There was light rust over much of the midportion of the strand with two 1-in. spots of heavy rusting, one 17 in. from the landward end and the other 13 in. from the seaward end.

(4) Internal versus external: The rust on the center wire exactly matched that on the outer wires for both ends.

b. Strand 2.

(1) Landward end: External corrosion extended for 55 in. from the end (0-55 in. = heavy).

(2) Seaward end: External corrosion extended for 3 in. from the end (0-3 in. = heavy).

(3) Rest of strand: The rusting was heavy over most of the midsection of this strand, like that described above for the landward end of this strand. The only section that was lightly rusted was close to the seaward end.

(4) Internal versus external: The center wire was heavily rusted where the outer wires were rusted for 55 in. from the landward end and lightly rusted for the remainder of the strand.

c. Strand 3.

(1) Landward end: External corrosion extended for 18 in. from the end (0-17 in. = heavy; 17-18 in. = moderate).

(2) Seaward end: External corrosion extended for 3 in. from the end (0-2 in. = heavy; 2-3 in. = moderate).

(3) Rest of strand: At a spot 27 in. from the landward end, there was a patch of heavy rusting 2 in. long. The rest of the strand was mildly rusted. At the landward end the wires of this strand were badly twisted and bent.

(4) Internal versus external: At the isolated spot of rust 27 in. from the landward end, the center wire became heavily rusted. The rusting on the center wire to either side of this area was light. At the landward end where the outer wires were twisted and bent, the center wire was missing from the length of the twisted section. The rust at the seaward end was light.

d. Strand 4.

(1) Landward end: External corrosion extended for 18 in. from the end (0-5 in. = heavy; 5-15 in. = moderate; 15-18 in. = light).

(2) Seaward end: External corrosion extended for 3 in. from the end (0 to 1/2 in. = heavy; 1/2 to 3 in. = moderate).

(3) Rest of strand: There were light intermittent areas of rust on the midportion of the strand, but overall the rusting was light.

(4) Internal versus external: At the landward end the heavy rusting on the center wire extended 2 in. farther into the beam than did that on the outer wires; on the rest of the strand the corrosion essentially matched that on the outer wires.

e. Strand 5.

(1) Landward end: External corrosion extended for 30 in. from the end (0-30 in. = heavy).

(2) Seaward end: External corrosion extended for 7 in. from the end (0-2 in. = heavy; 2-5 in. = moderate; 5-7 in. = light).

(3) Rest of strand: At 28 in. from the landward end there was a spot of heavy rust 1 in. long; otherwise there were only light spots of rusting.

(4) Internal versus external: At the seaward end there was moderate to heavy rusting from 0 to 7 in., after which the rust became light. For the 30 in. at the landward end, the center wire was heavily rusted.

f. Strand 6.

(1) Landward end: External corrosion extended for 7 in. from the end (0 to 2-1/2 in. = heavy; 2-1/2 to 7 in. = moderate).

(2) Seaward end: External corrosion extended for 7 in. from the end (0 to 2-1/2 in. = heavy; 2-1/2 to 5 in. = moderate; 5-7 in. = light).

(3) Rest of strand: From 14 to 24 in. from the seaward end, there was light to moderate rusting on the mid-portion of the strand.

(4) Internal versus external: The corrosion on the center wire matched that on the outer wires. In general, the rusting was light with the exception of the extreme 2-1/2 in. at each end.

g. Strand 7.

(1) Landward end: External corrosion extended for 7 in. from the end (0-3 in. = heavy; 3-7 in. = moderate).

(2) Seaward end: External corrosion extended for 8 in. from the end (0-3 in. = heavy; 3-6 in. = moderate; 6-8 in. = light).

(3) Rest of strand: There were two spots of heavy rust on the midsection of this strand, one a 3-in. rust spot 18 in. from the seaward end and the other a 1-in.-long spot 29 in. from the seaward end.

(4) Internal versus external: The rusting on the center wire was heavy at both ends, matching the external corrosion on the strand. At the two heavy spots on the midportion of the strand, the center wire had heavy corrosion.

h. Strand 8.

(1) Landward end: External corrosion extended for 9 in. from the end (0-4 in. = heavy; 4-9 in. = moderate).

(2) Seaward end: External corrosion extended for 8 in. from the end (0-7 in. = heavy; 7-8 in. = moderate).

(3) Rest of strand: On the midportion of the strand there was a 26-in.-long section that had 10 in. of heavy, 10 in. of moderate, and 6 in. of light corrosion. Two of the wires were broken in this area due to heavy corrosion.

(4) Internal versus external: The inner wire had corrosion over the entire length. At both ends the corrosion of the center wire was heavy and matched that of the outer wires. Throughout the midportion the corrosion was light to moderate.

i. Strand 9.

(1) Landward end: External corrosion extended for 10 in. from the end (0-4 in. = heavy; 4-10 in. = moderate).

(2) Seaward end: External corrosion extended for 7 in. from the end (0-4 in. = heavy; 4-7 in. = moderate).

(3) Rest of strand: There was light rusting over the entire midportion of this strand with heavy rust spots 1 in. long at 13, 22, and 29 in. from the seaward end.

(4) Internal versus external: The corrosion on the center wire matched that on the outer wires.

14. The following tabulation summarizes the corrosion to the strands of beam 13.

	Extent of Corrosion*		
Strand	Landward End	Seaward End	Rest of Strand
1	4-H 3-M	2-H 7-M	Light rust over rest of strand. Two 1-in. heavy spots
2	55-H	3-H	Most of the midspan heavily rusted
3	17-H 1-M	2-H 1-M	Generally light rust. At 27 in. from the landward end, a 2-in.-long heavily rusted area

(Continued)

* 4-H, 3-M denotes heavy corrosion on the first 4 in. and light corrosion on the next 3 in.

Strand	Extent of Corrosion: Landward End	Seaward End	Rest of Strand
4	5-H 10-M 3-L	1/2-H 2-1/2-M	Light intermittent rust on all the wires
5	30-H	2-H 3-M 2-L	Light rust over rest of wires. At 28 in. from landward end, a 1-in. heavy rust spot
6	2-1/2-H 4-1/2-M	2-1/2-H 2-1/2-M 2-L	From 14 to 24 in. from seaward end, light to moderate rust
7	3-H 4-M	3-H 3-M 2-L	Two 1-in.-long spots of heavy rust; rest only lightly rusted
8	4-H 5-M	7-H 1-M	In 26-in.-long section, 10 in. of heavy, 10 in. of moderate, and 6 in. of light rust; two broken wires due to heavy corrosion
9	4-H 6-M	4-H 3-M	Light rust over entire section. 1-in. spots of heavy rust at 13, 22, and 29 in. from landward end

15. External corrosion on the strands of beam 13 was generally heavy for the first 5 in. from the landward end; then the corrosion became moderate. Strands 2, 3, and 5 exhibited heavier corrosion for greater distances into the beam, the greatest being strand 2 with heavy corrosion for 55 in.; however, basically the corrosion beyond 30 in. became light and intermittent. At the seaward end of the strands, the corrosion was generally heavy for less than 4 in. and then became moderate to 8 in. The centers of the strands were in most cases lightly corroded with intermittent heavy rust spots at various distances from the ends. Strands 2 and 8 had extended lengths of moderate and heavy rusting.

16. The intensities of rusting on the center wires of the beam 13 strands matched those on the external wires in all cases except the one for the landward end of strand 4. Here the center wire was heavily corroded for 2 in. farther into the beam than were the outer wires. Photos 8a-8c show the relation between the outer wires and the inner wire of strands 3, 7, and 8 in beam 13. Although the rusting is

difficult to see because of the lack of contrast, these photographs show how the rusting of the inner wire matches that of the outer wires. In each photograph, the wires are more heavily corroded in the right half of the picture.

Beam 21

17. The following subparagraphs describe the corrosion on the steel strands examined from beam 21.

a. Strand 1.

(1) Landward end: External corrosion extended to 12 in. from the end (0-9 in. = heavy; 9-11 in. = moderate; 11-12 in. = light).

(2) Seaward end.*

(3) Rest of strand: There were light intermittent spots of rust throughout the central portion of the strand.

(4) Internal versus external: Heavy corrosion existed on the center wire up to 12 in. from the landward end of the strand; there was light rust on the center strand throughout its entire length.

b. Strand 2.

(1) Landward end: External corrosion extended to 19 in. from the end (0-9 in. = heavy; 9-19 in. = moderate).

(2) Seaward end.*

(3) Rest of strand: There was light rust on the central portion of this strand over its entire length.

(4) Internal versus external: Moderate and heavy rusting on the center wire matched that on the outer wires to 19 in. from the landward end. The center wire had light rust throughout its entire length.

c. Strand 3.

(1) Landward end: External corrosion extended for 30 in. from the end (0-30 in. = heavy).

(2) Seaward end: External corrosion extended for 24 in. from the end (0-19 in. = heavy; 19-24 in. = moderate).

(3) Rest of strand: There were small rust spots less than 1/2 in. long over most of the midsection.

(4) Internal versus external: Internal corrosion at the

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* Portions of the strand were either destroyed by or not identified after structural testing.

landward end matched the external corrosion on the strand, and corrosion on the center wire in the midsection of the strand was light. The corrosion on the central wire at the seaward end extended 1/2 in. farther into the beam than did that on the outer wires.

d. Strand 4.

(1) Landward end: External corrosion extended for 9 in. from the end (0-9 in. = moderate).

(2) Seaward end: External corrosion extended for 22 in. from the end (0-4 in. = moderate; 4-22 in. = heavy).

(3) Rest of strand: From 30 to 42 in. from the landward end the external corrosion was heavy. On the rest of the midsection there was light rust.

(4) Internal versus external: The corrosion on the center wire matched that on the outer wires. Heavy corrosion existed on the center wire over 9 in. of the landward end and 22 in. of the seaward end. The midsection of the center wire had light rusting.

e. Strand 5.

(1) Landward end: External corrosion extended for 15 in. from the end (0-15 in. = moderate).

(2) Seaward end: External corrosion extended for 30 in. from the end (0-12 in. = moderate; 12-30 in. = heavy).

(3) Rest of strand: From 20 to 30 in. from the landward end the rusting was heavy. The rest of the midsection was lightly rusted.

(4) Internal versus external: The corrosion on the center wire was the same as that on the outer wires. The rusting was heavy at both ends and also from 20 to 30 in. from the landward end. The remaining rust on the center wire was light.

f. Strand 6.

(1) Landward end: External corrosion extended for 10 in. from the end (0-2 in. = heavy; 2-4 in. = light; 4-10 in. = heavy).

(2) Seaward end: External corrosion extended for 20 in. from the end (0-7 in. = heavy; 7-20 in. = moderate).

(3) Rest of strand: The entire central section from 10 in. from the landward end to 20 in. from the seaward end was heavily corroded. The steel was so deteriorated that at 48 in. from the landward end two of the outer wires were broken.

(4) Internal versus external: There was heavy corrosion over most of the central wire in this strand. The only area that had less than heavy corrosion was at 10 in. from the landward end, where the corrosion was moderate. At the point 48 in. from the landward end where the outer wires were broken, it was also found that the central wire had been broken due to excessive corrosion. The central wire was also broken at a point 27 in. from the landward end.

g. Strand 7.

(1) Landward end: External corrosion existed for 12 in. from the end (0-12 in. = heavy).

(2) Seaward end.*

(3) Rest of strand: There was moderate corrosion on the wires in the midsection of this strand. This strand was tension-tested and left in four sections, thus hindering evaluation.

(4) Internal versus external: At the landward end the internal wire was corroded to the same depth and degree as were the outer wires. There was heavy corrosion for 12 in. from the end of the strand. Corrosion on the rest of the strand was difficult to catalog, but what appeared to be the central wire was moderately to heavily corroded.

h. Strand 8.

(1) Landward end: External corrosion extended for 12 in. from the end (0-6 in. = heavy; 6-12 in. = moderate).

(2) Seaward end: External corrosion extended for 10 in. from the end (0-4 in. = light; 4-10 in. = moderate).

(3) Rest of strand: From 31 to 50 in. from the landward end the corrosion was moderate.

(4) Internal versus external: The corrosion of the center wire matched that of the outer wires at both ends, and in the midsection the corrosion was heavier 31-50 in. from the landward end than anywhere else in the middle.

i. Strand 9.

(1) Landward end: External corrosion extended for 4 in. from the end (0-4 in. = heavy).

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* Portions of the strand were either destroyed by or not identified after structural testing.

(2) Seaward end: External corrosion extended for 60 in. from the end (0-6 in. = moderate; 6-60 in. = heavy).

(3) Rest of strand: Most of the central portion of the strand was heavily rusted and has been described above. The rest of the strand was lightly corroded.

(4) Internal versus external: Heavy corrosion on the center wire was identical to that found on the outer wires. From 0 to 60 in. the seaward end was heavily corroded, as was the landward end from 0 to 4 in.

18. The following tabulation summarizes the corrosion to the strands of beam 21.

	Extent of Corrosion*		
Strand	Landward End	Seaward End	Rest of Strand
1	9-H 2-M 1-L	Not available	Light intermittent rust throughout
2	9-H 10-M	Not available	Light intermittent rust throughout
3	30-H	19-H 5-M	Small rust spots 1/2 in. long over most of section
4	9-M	4-M 18-H	Heavy corrosion 30-42 in. from landward end; light rust over rest of section
5	15-M	12-M 18-H	Heavy rust 20-30 in. from landward end; light rust over rest of section
6	2-H 2-L 6-H	7-H 13-M	From 10 in. from the landward end to 20 in. from the seaward end, entire strand heavily corroded
7	12-H	Not available	Moderate corrosion on most of midsection
8	6-H 6-M	4-L 6-M	Moderate corrosion 31-50 in. from the landward end
9	4-H	6-M 54-H	Central part of the strand heavily rusted

* 9-H, 2-M, 1-L denotes heavy corrosion on the first 9 in., moderate on the next 2 in., and light on the next 1 in. of the strand.

19. The length of external corrosion on the strands of beam 21

was somewhat less than that on the strands of beam 13; however, the intensity of the rusting was greater. Heavy rusting at the landward end generally extended to 10-12 in. from the end of the beam. Then the rusting became moderate and was considered light after 15 in. The only exception was strand 3, which was heavily corroded to 30 in. from the end of the strand. The rust at the seaward end was much more extensive on the strands of beam 21 than that on the strands of the seaward end of beam 13. The rust generally extended inward from the end of the beam for more than 20 in. and in one case extended to 60 in. from the end of the strand. The rust was categorized as heavy over most of the corroded length, but the heavy corrosion occurred away from the end of the strand. Strands 4, 5, 8, and 9 had moderate rust at the ends and heavy rust farther into the strand.

20. Corrosion on the central section of the strands in beam 21 was to a large extent heavy, as described in the previous paragraph. Of the spots not covered by the description in paragraph 19, most were lightly rusted. Strands 4 and 5 had heavy rust for 10 and 12 in., respectively, and the entire central section of strand 6 was heavily rusted.

21. The interior wire of this beam showed the same results as did the interior wire of beam 13. The corrosion of the center wire matched that of the outer wires. Photos 9a-9d show the center wire in relation to the outer wires of strands 4, 6, 8, and 9. In all cases where the outer wires were heavily rusted, the inner wires were also, and where the outer wires were lightly rusted, the center wires were also.

22. The rusting on the strands was heavier in beam 21 than in beam 13. Photo 10 shows wires from strand 6 of beam 21 at a point 24 in. from the seaward end of the beam where two outer wires and the inner wire were corroded. This result was also shown in the structural testing of the strands of beams 13 and 21.

23. Roshore[3] found that the internal corrosion of the strand had progressed farther from the ends of the beam than the external corrosion. His observations showed that the center wire, and the internal surfaces of the six external wires, were rusted for a longer length inward from the beam ends than the external surfaces of the six external wires. His

conclusions were that water and oxygen progressed along the voids surrounding the center wire and reached farther into the beam internally than externally. A similar observation was not made during the work reported here. The cause of the differences in observations is not known. Many factors were different between the pairs of beams reported on here and previously.[3] The prestressing loads for beams studied previously,[3] Nos. 4 and 8, were approximately 1 percent and 70 percent of ultimate strand strength, respectively. Beams 13 and 21 studied in this work were both loaded to 70 percent of ultimate strength of the prestressing strands. Beams 4 and 8 were placed at Treat Island without being flexurally loaded, while beams 13 and 21 were loaded in flexure to 108 percent and 100 percent of the prestressing load to balance the compressive stresses placed on the concrete at the time of prestress transfer. An additional difference was that beams 4 and 8 were returned to the WES in 1968 while beams 13 and 21 remained at the exposure site until 1974.

24. One possible reason why the greater extent of corrosion was not found in this work is that the higher level of tensile stress in the strands caused by the additional flexural loading of beams 13 and 21 may have increased the degree to which the bond was destroyed along the strand. Also, the additional period of 6 years of exposure to freezing and thawing may have increased the degree of bond failure to the point where the progress of water and oxygen was the same as that along the center wire.

Tensile Strength and Elastic Properties of Strands

25. Four strands from each of the two beams were tension-tested to determine ultimate tensile strength, ultimate tensile stress, total elongation, and load at 1 percent elongation. The testing was conducted in general accordance with the applicable portions of ASTM Designation: A 416-68 (Reference 5) and the results compared with the stated specifications for this type of prestressing strand. The specifications are as follows:

Minimum load at 1 percent extension:	7650 lb
Minimum ultimate load:	9000 lb
Minimum total elongation:	3.5 percent

Beam 13

26. The strands tested from beam 13 were considered to be the least corroded of the nine strands of that beam. Only two of the strands met the requirements of ASTM A 416-68 for ultimate load, and none of the specimens passed the requirements for minimum percent total elongation. The results obtained are given below:

Strand	Ultimate Load, lb	Ultimate Stress psi	Load at 1 Percent Extension lb	Total Elongation percent
1	9090	258,239	8300	2.11*
3	7580**	215,341	--†	0.80*
6	9180	260,795	7700	2.85*
9	8300**	235,795	8250	1.05*

* Strand did not meet ASTM minimum requirements for total elongation.

** Strand did not meet ASTM minimum requirements for ultimate load.

† Strand did not reach 1 percent extension before failure.

Beam 21

27. The four strands of beam 21 that were tension-tested had the stress-strain characteristics presented below. All four strands failed to meet ASTM requirements for ultimate load, load at 1 percent extension, and total elongation.

Strand	Ultimate Load, lb	Ultimate Stress psi	Load at 1 Percent Extension lb	Total Elongation percent
1	7440*	211,364	--**	0.85†
2	6080*	172,727	--**	0.62†
5	4370*	124,147	--**	0.34†
7	7880*	223.864	--**	0.87†

* Strand did not meet ASTM minimum requirements for ultimate load.

** Strand did not reach 1 percent extension before failure.

† Strand did not meet ASTM minimum requirements for total elongation.

A typical stress-strain curve for each beam is presented in Plate 1.

Depth of Carbonation

28. Slices of concrete from the top halves of beams 13 and 21 were tested for depth of carbonation. The slices were approximately 5 in. long, 4 in. wide (the full width of the beam), and 1/4 in. thick. The slices were taken from the top of each beam down to the level of the top row of prestressing strands. Each section was treated with a 1 percent anhydrous phenolphthalein solution. Phenolphthalein, being an acid-base indicator, turns pink in the presence of alkalies with a pH greater than 8.2 (Reference 6) and remains clear in the presence of acids or alkalies with a pH lower than 8.2. By coating the cross-sectional slices with this indicator, the depth of carbonation can be visibly determined.

29. In Photos 11 and 12 it can be seen that the depth to which carbonation penetrated was less than 1/16 in. In most cases the phenolphthalein indicator turned red at the outer surface of the beam. This was true of slices from both beams. In these photographs the darker areas represent the concrete that had not been carbonated, and the lighter concrete areas, if there are any, near the surface of the beam represent the depth of carbonation. It should be noted that the aggregate is light because it is limestone and a carbonate aggregate. The approximate locations of the sections are given below:

Beam-Section	Distance from Landward End in.	Depth from Top of Beam, in.
13-1	46	1
13-2	46	2
13-3	46	3
13-4	46	4
13-5	46	5
21-1	24	1
21-2	24	2
21-3	24	3
21-4	24	4
21-5	24	5

30. This test was previously conducted on beam 8 from the same

Depth of Carbonation

28. Slices of concrete from the top halves of beams 13 and 21 were tested for depth of carbonation. The slices were approximately 5 in. long, 4 in. wide (the full width of the beam), and 1/4 in. thick. The slices were taken from the top of each beam down to the level of the top row of prestressing strands. Each section was treated with a 1 percent anhydrous phenolphthalein solution. Phenolphthalein, being an acid-base indicator, turns pink in the presence of alkalies with a pH greater than 8.2 (Reference 6) and remains clear in the presence of acids or alkalies with a pH lower than 8.2. By coating the cross-sectional slices with this indicator, the depth of carbonation can be visibly determined.

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Beam-Section	Distance from Landward End in.	Depth from Top of Beam, in.
13-1	46	1
13-2	46	2
13-3	46	3
13-4	46	4
13-5	46	5
21-1	24	1
21-2	24	2
21-3	24	3
21-4	24	4
21-5	24	5

30. This test was previously conducted on beam 8 from the same

series of beams and the results reported in Report 3 (Reference 3); the results of both tests are similar.

Degree of Chloride Contamination

31. From each beam, samples of concrete were taken and tested for degree of chloride contamination. The concrete samples were 1/4 in. thick and were taken from beam 13 at depths of 5/8, 1-3/8, 2-5/8, and 3-3/8 in. from the surface and labeled samples 1-4, respectively; slices were taken from beam 21 at depths of 5/8, 1-5/8, 2-3/8, and 3-1/8 in. from the surface and labeled samples 1-4, respectively. The location of each sample and chloride content in percent by weight of concrete are presented in the following tabulation.

Beam-Sample	Depth from Nearest Surface of Beam, in.	Distance from Landward End in.	Chlorides, % by Weight of Concrete
13-1	1/2	30	0.803
13-2	1-3/8	30	0.585
13-3	2-5/8	30	0.689
13-4	3-3/8	30	0.762
21-1	5/8	26	0.839
21-2	1-5/8	26	0.582
21-3	2-3/8	26	0.471
21-4	3-1/8	26	0.443

32. The concrete was analyzed for chloride content using the silver nitrate titration procedure described by Berman.[7] The chloride contents reported ranged from 0.443 to 0.839 percent by weight of concrete. Plate 2 shows that chloride content decreases with depth in beam 21 but not in beam 13, where an initial decline was followed by an increase. This relation was previously observed by Roshore (Reference 3) in specimens from St. Augustine.

PART IV: CONCLUSIONS

33. The external corrosion of the steel strands in both beams was heavier at the ends than in the midsections of the strands. Although in some strands extensive heavy corrosion was found on the midsection, generally the midsection was only lightly rusted. Since it was noted that small pieces of cement paste were attached to the strands in areas of light rusting and no cement paste was on the strands in areas of heavy corrosion, it was concluded that the areas in which there was good bond between the cement paste and steel were protected against heavy rusting.

34. From the structural tests conducted on the most sound strands of each beam, it was concluded that the extent of corrosion on the strands of pretensioning steel was severe enough to reduce the tensile properties of the steel to an unacceptable level.

35. There was only one case in which the corrosion on the center wire extended farther into the beam than did the corrosion on the outer wires. In all the other cases, the intensity and length of the rust along the center wire matched that along the outer wires. From these results, it was concluded that (a) water traveled along the length of the strand only where there was little or no bond between the cement paste and steel, (b) corrosion of the center wire was the result of water and oxygen seeping into the strand from the cement paste-steel interface rather than from progression along the central strand, and (c) corrosion due to water being pulled farther into the strand length by the center wire did not exist. This conclusion differs from that given by Roshore.[3] The difference may be due in large part to differences in load level applied to the beams as these affected the quality of bond between paste and steel over a long exposure time.

36. Results of tests conducted to ascertain the depth of carbonation by coating sliced sections with phenolphthalein indicator revealed carbonation depths to 1/16 in. or less. It was therefore concluded that carbonation was not a determining factor in the corrosion of the steel.

37. Results of tests for degree of chloride contamination revealed chloride contents ranging from 0.443 to 0.839 percent by weight

of concrete. In beam 21 the chloride content decreased with depth from the surface; in beam 13 an initial decline in concentration with depth for approximately 1 to 2 in. was followed by an increase (see Plate 2). From these results it was concluded that sufficient chlorides were present in the concrete to be a major cause of corrosion of the steel.

38. It is also concluded that the 3- by 5- by 1/2-in.-thick epoxy end protection pads did not adequately protect the ends of the strands from corrosion.

39. Sufficient corrosion data were not obtained to establish a relationship between durability and intensity of loading.

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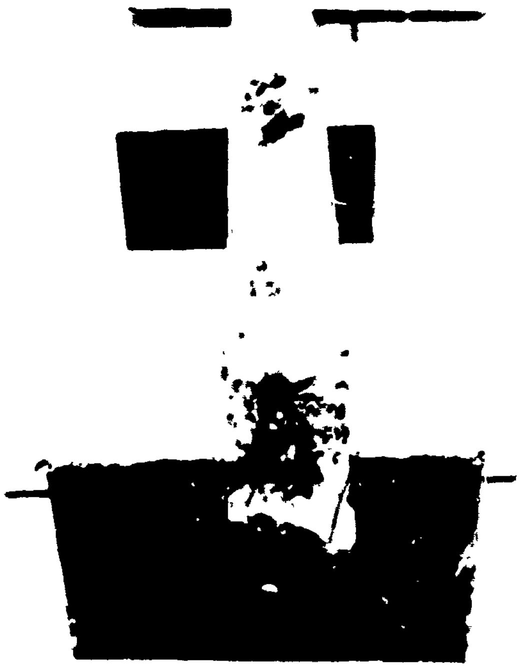
3. __________, "Durability and Behavior of Prestressed Concrete Beams; Laboratory Tests of Weathered Pretensioned Beams," Technical Report No. 6-570, Report 3, Oct 1971, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

4. O'Neil, E. F., "Durability and Behavior of Prestressed Concrete Beams; Laboratory Tests of Weathered Posttensioned Beams" (in preparation), Technical Report No. 6-570, Report 4, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

5. American Society for Testing and Materials, "Standard Specifications for Uncoated Seven-Wire Stress-Relieved Strand for Prestressed Concrete," Designation: A 416-68, <u>1969 Book of ASTM Standards</u>, Part 4, Jan 1969, Philadelphia, Pa., pp 559-562.

6. Chemical Rubber Company, "Handbook for Chemistry and Physics," 47th ed., p D-82.

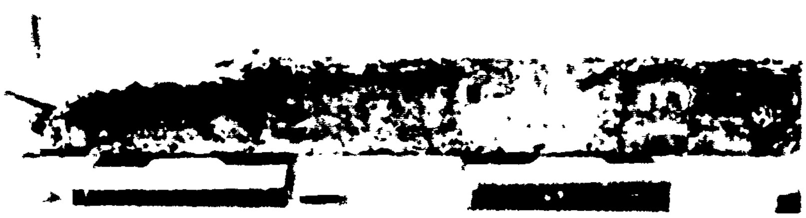
7. Berman, H. A., "Determination of Chloride in Hardened Portland Cement Paste, Mortar, and Concrete," <u>Journal of Materials</u>, American Society for Testing and Materials, Vol 7, No. 3, Sep 1972, pp 330-335.



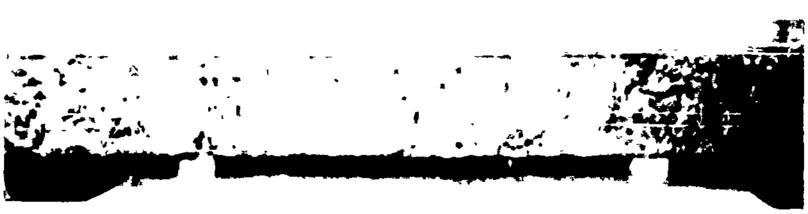
a. Landward end

b. Seaward end

Photo 1. End views of beam 13

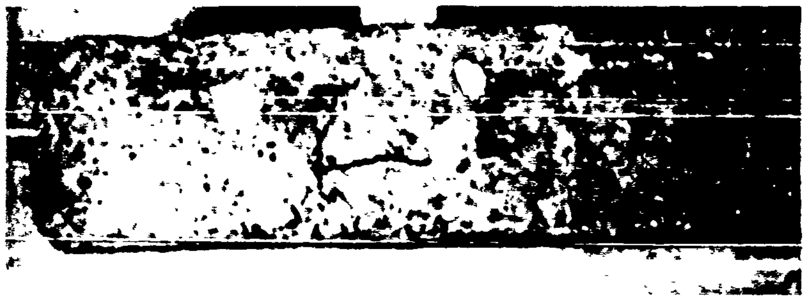


a. Beam 13



b. Beam 21

Photo 2. Spalling damage



a. Landward end

b. Seaward end

Photo 3. End views of beam 21

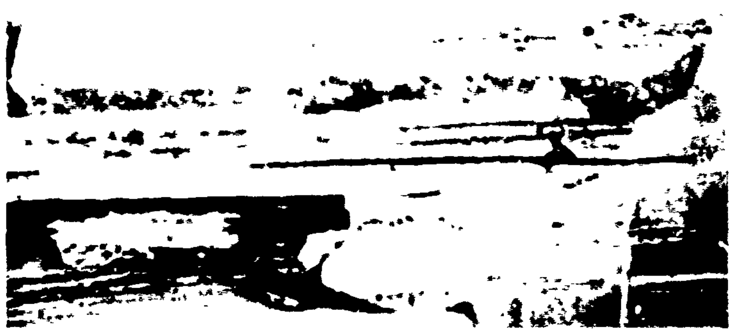
a. Beam 13

b. Beam 21

Photo 4. Exposed steel strands

a. Landward end condition b. Seaward end condition

Photo 5. Rusting and staining to beam 13

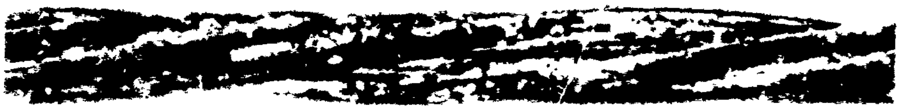


a. Landward end condition

b. Seaward end condition

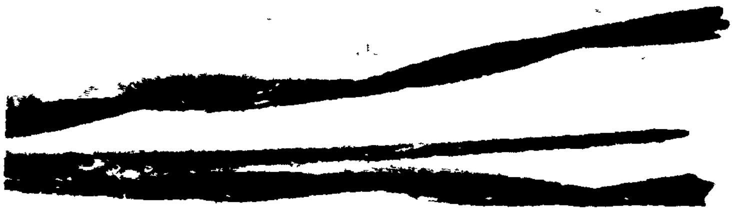
Photo 6. Rusting and staining to beam 21

a. Heavy



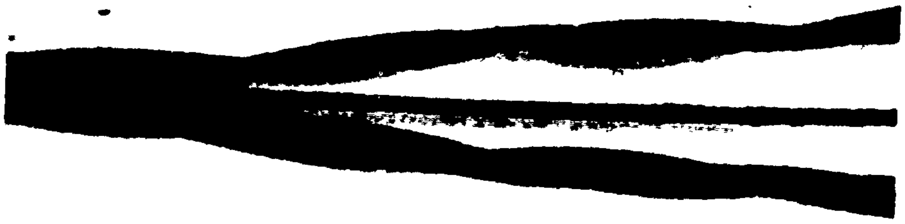
b. Light

Photo 7. Examples of strand corrosion



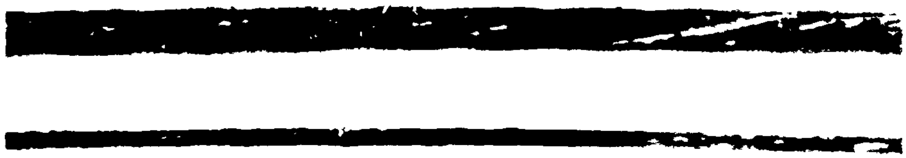
a. Strand 3 at seaward end

b. Strand 7 at 10 in. from landward end



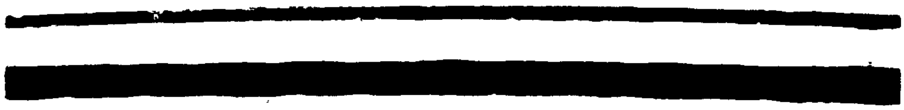
c. Central section of strand 8 at 17 in. from landward end

Photo 8. Relation between outer wires and inner wire of some strands in beam 13

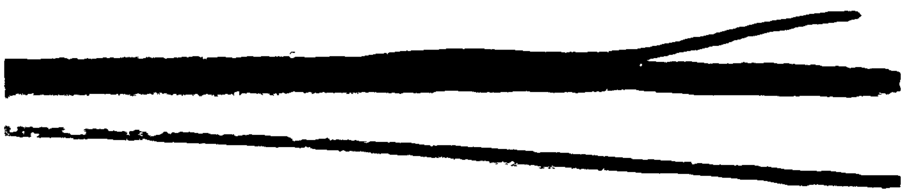


a. Strand 4 at 7 in. from seaward end

b. Strand 6 at 15 in. from landward end



c. Strand 8 at 10 in. from seaward end



d. Strand 9 at landward end

Photo 9. Relation between outer wires and inner wire of some strands in beam 21

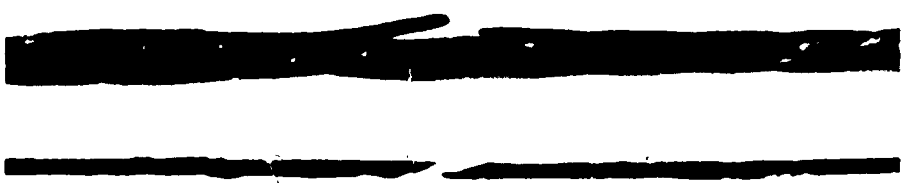
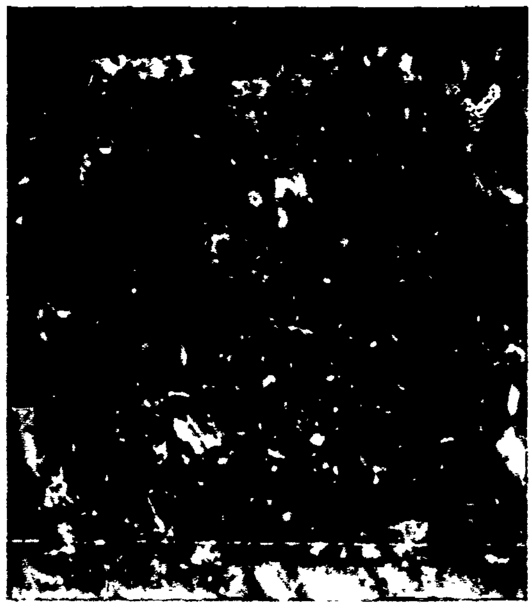


Photo 10. Corroded wires of strand 6 of beam 21

a. Section 1



b. Section 2

c. Section 3

Photo 11. Depth of carbonation penetration in beam 13
(sheet 1 of 2)

d. Section 4

e. Section 5

Photo 11 (sheet 2 of 2)

a. Section 1

b. Section 2

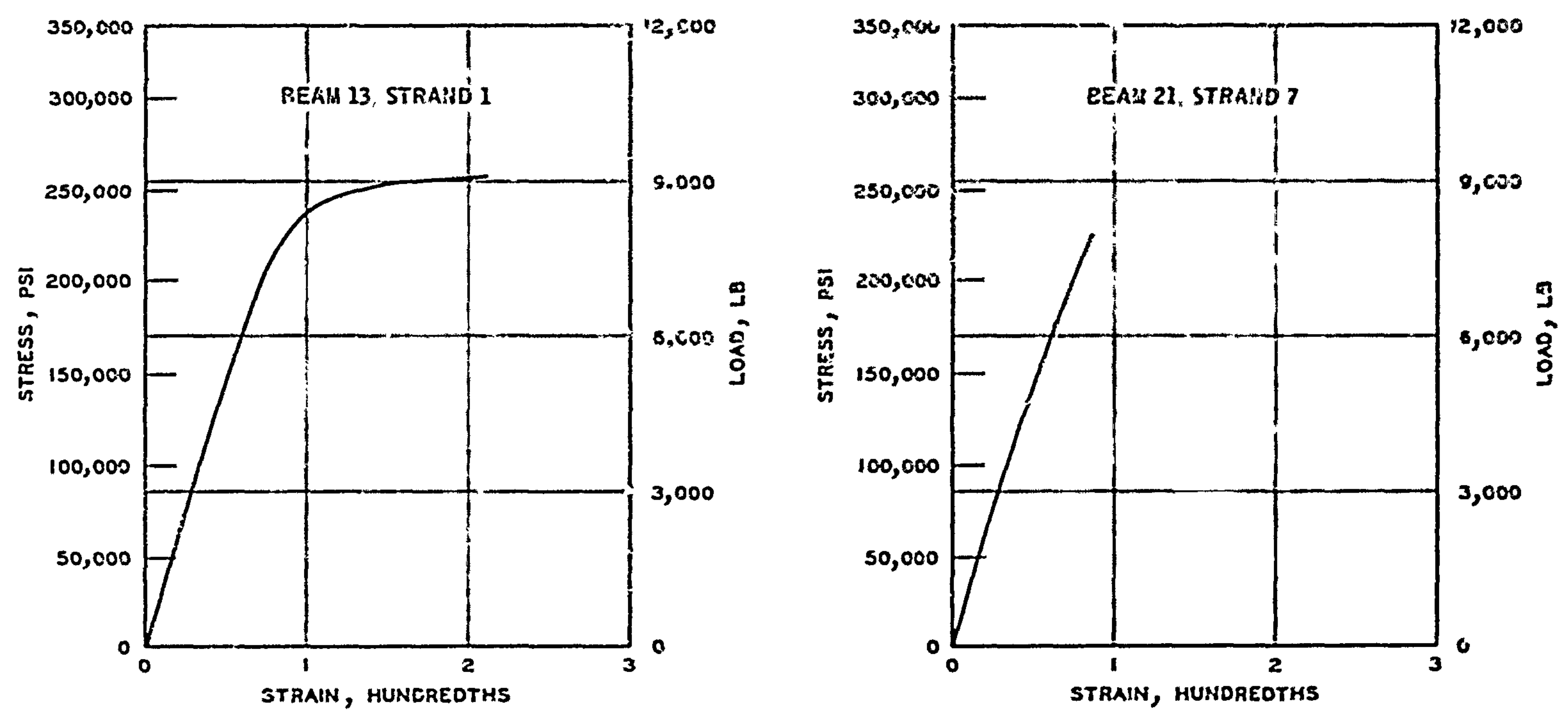
c. Section 3

Photo 12. Depth of carbonation penetration in beam 21 (sheet 1 of 2)

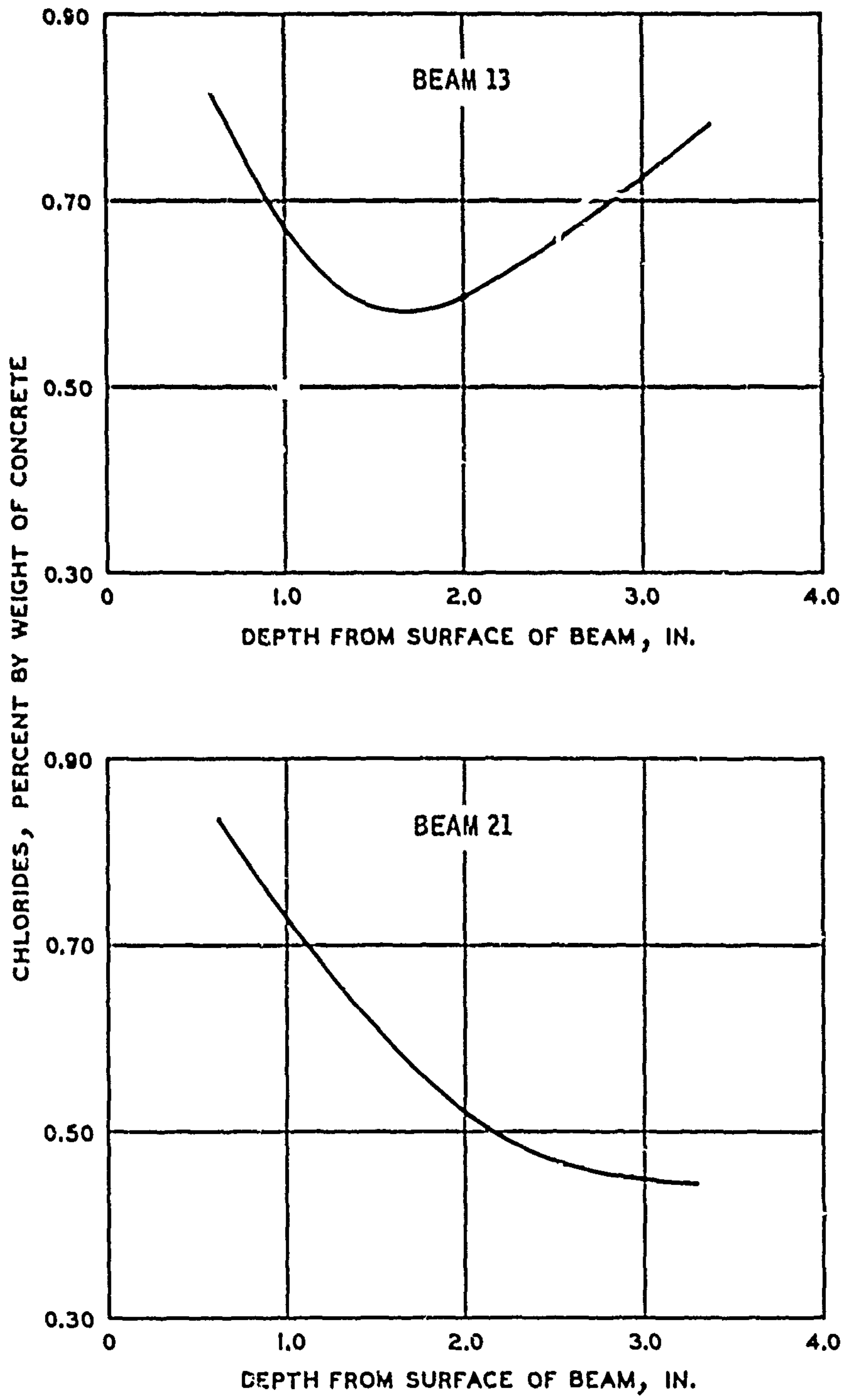
d. Section 4

e. Section 5

Photo 12 (sheet 2 of 2)



STRESS-STRAIN CURVES



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Durability and behavior of prestressed concrete beams; Report 5: Laboratory tests of weathered pretensioned beams, by Edward F. O'Neil. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1976.
1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Technical report 6-570, Report 5)
Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under Work Unit 01 04 01/31133.
Includes bibliography.

1. Concrete beams. 2. Concrete durability. 3. Corrosion. 4. Laboratory tests. 5. Prestressed concrete. 6. Pretensioning. 7. Reinforcing steels. 8. Tensile strength. I. U. S. Army. Corps of Engineers. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Technical report 6-570, Report 5)
TA7.W34 no.6-570 Report 5